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THE EFFECT OF FRICTION ON INDENTER FORCE AND PILE-UP IN NUMERICAL SIMULATIONS OF BONE NANOINDENTATION

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1. ABSTRACT

Nanoindentation is a useful technique for probing the mechanical properties of bone, and finite element (FE) modeling of the indentation allows inverse determination of elasto-plastic constitutive properties. However, FE simulations to date have assumed frictionless contact between indenter and bone. The aim of this study was to explore the effect of friction in simulations of bone nanoindentation. Two dimensional axisymmetric FE simulations were performed using a spheroconical indenter of tip radius 0.6μm and angle 90°. The coefficient of friction between indenter and bone was varied between 0.0 (frictionless) and 0.3. Isotropic linear elasticity was used in all simulations, with bone elastic modulus E=13.56GPa and Poisson's ratio ν=0.3. Plasticity was incorporated using both Drucker-Prager and von Mises yield surfaces. Friction had a modest effect on the predicted force-indentation curve for both von Mises and Drucker-Prager plasticity, reducing maximum indenter displacement by 10% and 20% respectively as friction coefficient was increased from zero to 0.3 (at a maximum indenter force of 5mN). However, friction has a much greater effect on predicted pile-up after indentation, reducing predicted pile-up from 0.27μm to 0.11μm with a von Mises model, and from 0.09μm to 0.02μm with Drucker-Prager plasticity. We conclude that it is important to include friction in nanoindentation simulations of bone.

2. INTRODUCTION

Nanoindentation is an established technique for probing the mechanical properties of materials at the nanoscale, and has recently been applied to investigate the mechanical properties of natural biomineralized tissues such as bone, scales, and teeth [1-9]. While the indenter force versus depth curve provides a basic indication of local tissue stiffness, more detailed information on the mechanical constitutive properties of the tissue under test can be inferred using a combination of high resolution 3D imaging to examine the indentation profile (including the degree of pile-up around the indenter), and Finite Element (FE) modelling of the indentation to inversely determine elasto-plastic constitutive properties for the material. However, FE simulations of bone nanoindentation to date have assumed frictionless contact between indenter and bone [7-9]. Given that the actual indenter-bone interface will be subjected to frictional forces, the aim of this study was to investigate the importance of incorporating friction at the interface between indenter and bone in numerical simulations of bone nanoindentation.

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3. METHODS

3.1 Geometry and FE Mesh

To explore the effect of friction in simulations of bone nanoindentation, two dimensional axisymmetric finite element simulations were performed based on an existing study by Mullins *et. al.* [7] using a spheroconical indenter of tip radius 0.6μm and angle 90°. The total FE domain was 60μm x 60μm (100 times the indenter tip radius). A graded mesh of reduced integration, linear 4-node axisymmetric elements (ABAQUS CAX4R) was used to discretise the domain. The FE mesh is shown in Fig. 1. A preliminary mesh sensitivity analysis was performed to ensure that the simulation results were insensitive to mesh size in the indenter tip region.

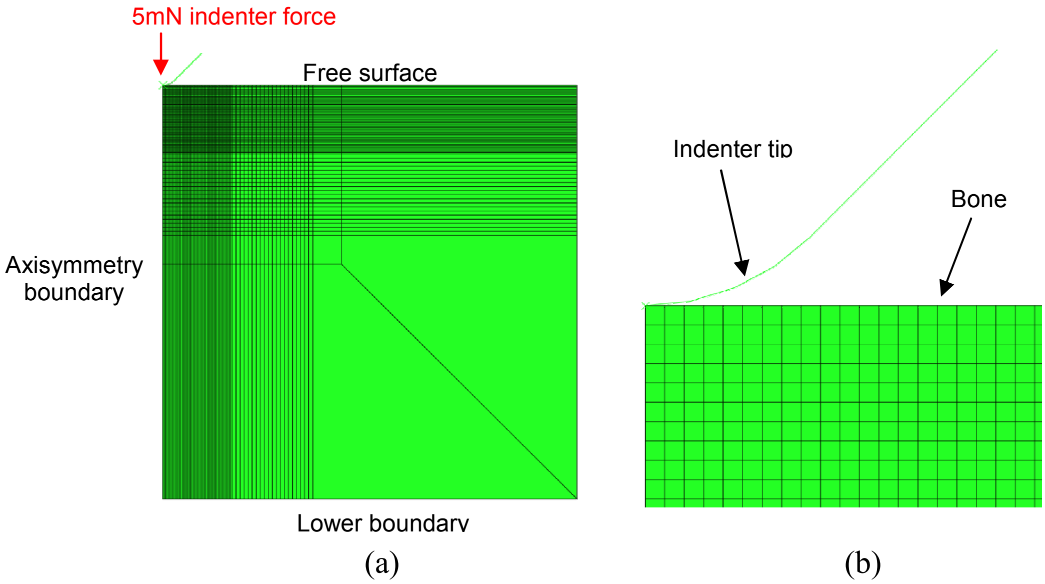

Fig 1. (a) Axisymmetric FE mesh showing boundary conditions and indenter force, (b) close-up view of mesh in the vicinity of indenter tip

3.2 Materials

Following Mullins *et. al.* [7], isotropic linear elasticity was used in all simulations with elastic modulus E=13.56GPa and Poisson's ratio ν=0.3. Plasticity was incorporated using both von Mises (σ_y=0.301 GPa, perfectly plastic) and Drucker-Prager (δ=122 MPa, β=46°) yield surfaces[3]. The indenter was assumed rigid.

3.3 Loads and boundary conditions

The model was loaded in two steps. The indenter was firstly subjected to a ramped 5mN compressive load, followed by unloading to zero indenter force, in order to observe the indentation left in the bone upon removal of the load. During these steps, the lower edge of the bone was constrained vertically. An axisymmetric boundary condition was used along the symmetry axis beneath the indenter tip. In order to explore the effect of

[3] σ_y is the uniaxial yield stress, δ is the cohesion, and β is the friction angle in the meridional plane.

interface friction, a range of friction coefficients were simulated between indenter and bone (μ= 0, 0.1, 0.2, 0.3). A penalty friction algorithm was used, and a 'hard' contact formulation was used in the normal direction.

3.4 Solution and post-processing

The models were solved using ABAQUS/Explicit version 6.7-1 (Simulia Inc, RI, USA). All simulations included the ABAQUS non-linear geometry capability (*NLGEOM) for finite deformations. The dependent variables investigated were (i) the predicted indenter force-displacement profile, (ii) the predicted degree of pile-up, and (iii) the predicted normal and shear stress distribution at the interface between indenter and bone.

4. RESULTS

Fig. 2 shows the effect of friction on the predicted force-indentation curves for the cases of von Mises and Drucker-Prager plasticity respectively. The figures show that friction had a modest effect on the predicted force-indentation curve for both von Mises and Drucker-Prager plasticity, reducing maximum indenter displacement by 10% and 20% respectively as friction coefficient was increased from zero to 0.3 (at a maximum indenter force of 5mN).

Fig. 3 shows the effect of friction on predicted pile-up after removal of the indenter. These figures show that friction has a large influence on predicted pile-up after indentation, with an increase in friction coefficient from 0 to 0.3 reducing predicted pile-up from 0.27μm to 0.11μm with a von Mises constitutive model, and from 0.09μm to 0.02μm with a Drucker-Prager yield surface. Fig. 4 shows contours of residual vertical displacement after removal of the indenter force, to illustrate the difference between the cases of greatest and least pile-up in this study (0.27μm pile-up with von Mises plasticity, μ=0; 0.02μm pile-up with Drucker-Prager plasticity and μ=0.3).

Figs. 5 and 6 compare the predicted normal and shear stress distributions along the indenter-bone interface for von Mises and Drucker-Prager plasticity models respectively, with friction coefficients of μ=0 and μ=0.3. The shear stress distribution for μ=0 is not shown because there are no shear stresses in the frictionless case.

5. DISCUSSION

Characterising the response of bone tissue to mechanical loading is essential to understanding how bone quality [10] changes in health and disease. Nanoindentation provides a powerful experimental technique to assess bone tissue mechanical resistance at the material level, and several recent studies have used FE models of nanoindentation to draw conclusions regarding the suitability of various candidate elasto-plastic constitutive models for bone tissue. However, to our knowledge all simulations to date have assumed frictionless contact between the indenter and the bone. The results of this study suggest that although changes in bone-indenter friction coefficient between 0 and 0.3 have only a moderate (10-20% change) effect on predicted indenter displacement at a given force, they have a much larger influence on predicted pile-up, with μ=0.3 reducing pile-up by 60% and 78% for the von Mises and Drucker-Prager cases respectively, compared to the frictionless case.

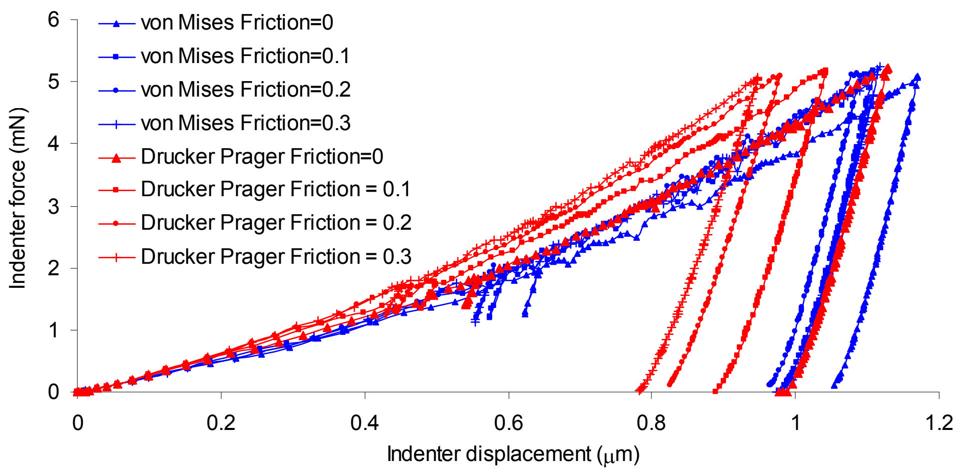

Fig 2. Effect of friction on predicted force-indentation curves

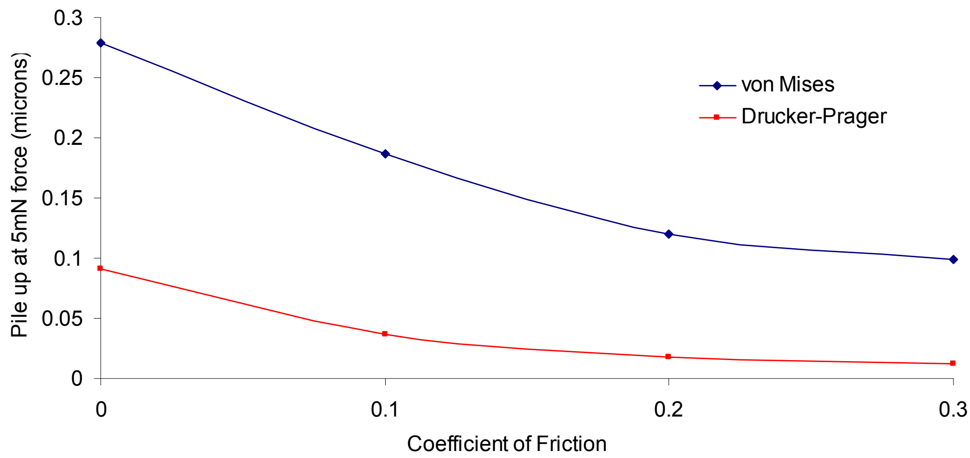

Fig 3. Effect of friction on predicted pile-up

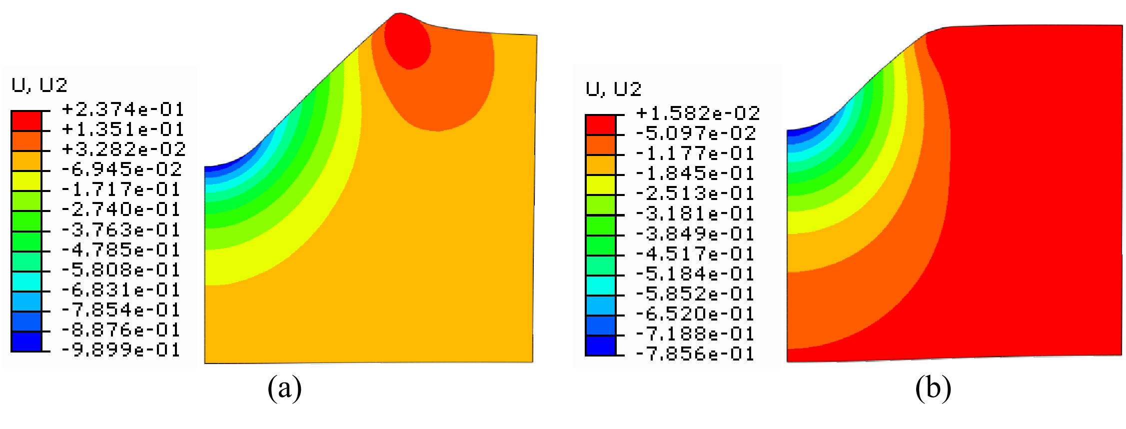

Fig 4. Contours of vertical displacement at 5mN indenter force for (a) von Mises plasticity with μ=0, (b) Drucker-Prager plasticity with μ=0.3

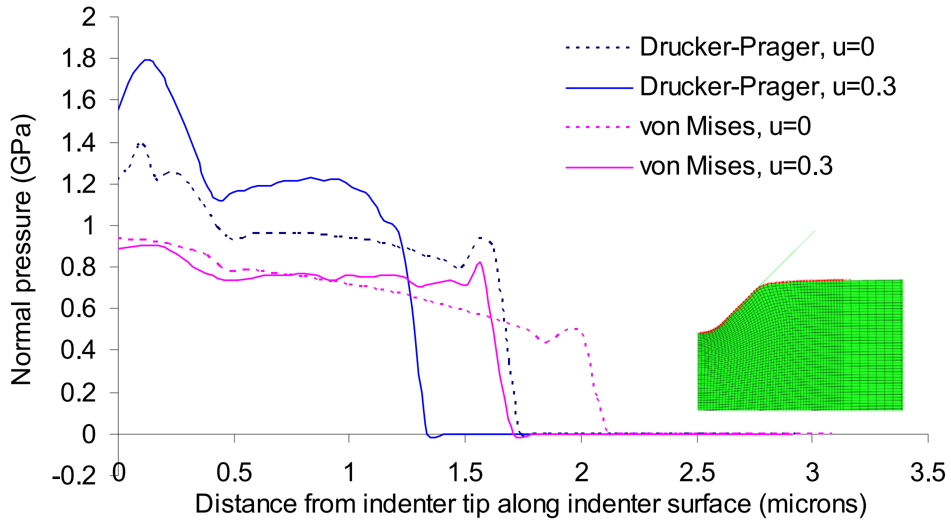

Fig 5. Interfacial normal pressure distribution along the indenter face at 5mN force

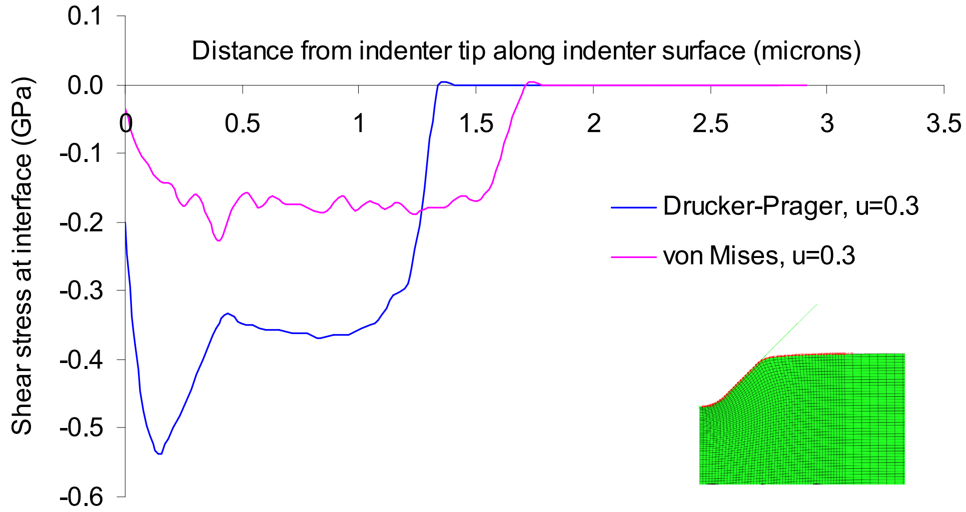

Fig 6. Interfacial shear stress distribution along the indenter face at 5mN force

The relevance of this finding depends on how close the actual friction coefficient between indenter and bone is to zero. If there is appreciable friction, then neglecting it in FE simulations could give an inaccurate picture of the suitability of a given elasto-plastic constitutive model to represent bone tissue. To our knowledge there is no published data on the friction coefficient between bone and diamond indenter tips. Although the interface will be lubricated by bone fluid, at the low loading rates and high contact pressures typical of indentation tests, the fluid may not appreciably reduce the transmission of shear stress between bone tissue and indenter. We note that previous studies on indentation of ductile metals have reported a strong friction effect [11,12], and that Cordey *et. al.* reported a metal-bone friction coefficient of 0.2±0.1 [13].

There are several limitations of the present study which could be addressed in future.

Firstly, we followed other authors in using isotropic material properties for the elastic portion of the bone constitutive response, although transverse isotropy would have provided a more realistic bone elastic response. Secondly, we did not investigate other indenter geometries (Berkovich, cube-corner, or spherical), only the sphero-conical indenter geometry used by Mullins *et. al.* [7] was modelled in this study.

We conclude that friction strongly affects predicted pile-up in nanoindentation simulations of bone, therefore it is important to include friction for inverse determination of bone tissue constitutive properties using FE simulation approaches.

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